

Gamma-Ray Observations of GRO J1655-40

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Abstract. The bright transient X-ray source GRO J1655-40 = XN Sco 1994 was observed by the OSSE instrument on the Compton Gamma Ray Observatory (GRO). Preliminary results are reported here. The initial outburst from GRO J1655-40 was detected by BATSE on 27 Jul 1994. OSSE observations were made in five separate viewing periods starting between 4 Aug 1994 and 4 Apr 1995. The first, third, and fifth observations are near the peak luminosity. In the second observation, the source flux had dropped by several orders of magnitude and we can only set an upper limit. The fourth observation is a weak detection after the period of maximum outburst. In contrast with other X-ray novae such as GRO J0422+32, the spectrum determined by OSSE is consistent with a simple power law over the full range of detection, about 50 – 600 keV. The photon spectral index is in the range of –2.5 to –2.8 in all of the observations. We set an upper limit on fractional rms variation of <5% in the frequency range 0.01 – 60 Hz. No significant narrow or broad line features are observed at any energy.

Key words: X-rays: stars – Stars: Individual: GRO J1655-40 – Gamma rays: observations

1. INTRODUCTION

We report on observations of GRO J1655-40 made with the Oriented Scintillation Spectrometer Experiment (OSSE) onboard the Compton Observatory (GRO) in the energy range from 50 – 600 keV, following discovery by BATSE (Zhang et al. 1994) on 27 July 1994. GRO J1655-40 is one of two X-ray novae, along with GRS 1009-45, which have been observed by OSSE to exhibit a power-law spectrum over this energy range. GRO J1655-40 is particularly interesting since it has been observed to have

super-luminal radio jets (Tingay et al. 1995, Hjellming et al. 1995) and radio flare occurring within 1–2 weeks after hard X-ray outbursts (Harmon et al. 1995). Its distance is estimated at 3.2 kpc (Hjellming et al. 1995, McKay et al. 1994, Bailyn et al. 1995a), and its mass is > 3.2 solar masses, implying it is a black hole system. The system is an eclipsing binary with a period of 2.62 days (Bailyn et al. 1995a).

2. Observation

The GRO spacecraft was reoriented four times permitting five OSSE observations of the transient from 4–9 August, 29 – 31 August, 7 – 13 December 1994, 20 December 1994 – 3 January, and 29 March–4 April 1995 (GRO viewing periods 336.5, 338, 405.5, 407 and 414.3 respectively). Each time the reorientation of the spacecraft was in response to a BATSE detection of an outburst from the source. The BATSE light curve through January 1995 is given by Harmon et al. (1995).

3. Results

Three of the five OSSE observations provide a strong detections of a soft power-law spectrum and are shown in Figure 1. An upper limit for emission is determined in the 29 – 31 August observation (VP 338) limited by possible source confusion with nearby 4U 1700-37. Nearby sources 4U 1700-37 and OAO 1657-415 may contribute some flux in the very lowest energy points in each of the observations. The flux estimate for 4U 1700-37 is based on the spectral shape and quiescent amplitude reported by Rubin et al. (1992) folded through the OSSE instrument response.

A simple power-law model provides a good overall fit to all of the data. The χ^2 per degree of freedom in the three fits shown in Figure 1 are 0.96, 0.88, and 0.97 respectively. Values are slightly less than 1.0 due to a small correction for systematic uncertainties in the measurements applied below 150 keV (7% at 50 keV, diminishing to 3%

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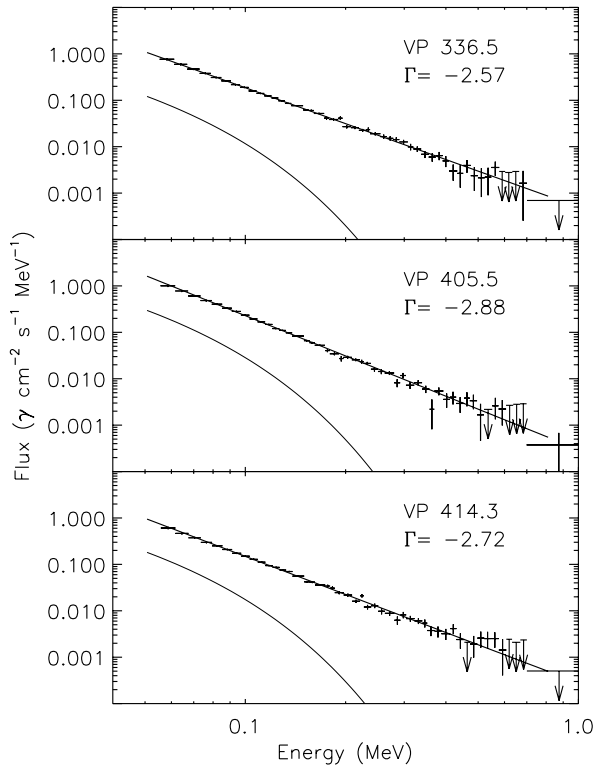


Fig. 1. Power law fits to the OSSE spectra of GRO J1655-40. Each viewing period represents a 5, 6, and 6 day exposure, respectively, near the maximum of each of three outbursts detected by BATSE. The lower curve in each panel represents an estimate of flux contributed from the nearby source 4U 1700-37 to the OSSE observation. 4U 1700-37 is not fully resolved from GRO J1655-40. The uncertainty in the spectral given in the three panels indices is less than ± 0.04 .

at 150 keV). An exponentially truncated power law provides a slightly better fit than the simple power law, in this case with an exceptionally high lower limit value of $kT \geq 665$ keV (95% confidence) fit through data from all three viewing periods. The F-test statistic does not demand the use of the additional degree of freedom in this model to fit the data. Comptonization models do not give an acceptable fit to the data. The model of Sunyaev & Titarchuk 1980 does not include relativistic terms that are required to produce photons at energies above a few 100 keV. The Titarchuk 1994 and Hua & Titarchuk 1995 models include the relativistic terms but are driven to optical depths much less than 10^{-3} to fit the data, at which point the diffusion approximation used in the model is no longer valid.

The fourth observation (VP 407) provided a weak detection of GRO J1655-40. This observation is complicated due to better exposure to 4U 1700-37 and the galactic plane than to GRO J1655-40. The contribution of 4U 1700-37 is minimized in the analysis by select-

ing data from half day intervals centered on the eclipse times of 4U 1700-37 (3.411652 ± 0.000026 day period, Haberl et al. 1989). The resulting detection is $7.2(\pm 1.8) \times 10^{-2} \gamma \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$ in a 55-144 keV energy band. This detection is not strong enough to place significant constraints on the spectral index of a power law fit. This detection is following a BATSE flare and implies that a weak hard X-ray emission persisted after this flare at or just below the BATSE sensitivity threshold.

4U 1700-37 eclipse time analysis has also been applied to viewing periods 336.5, 405.5, and 414.3 with no substantive change in fit parameters for GRO J1655-40.

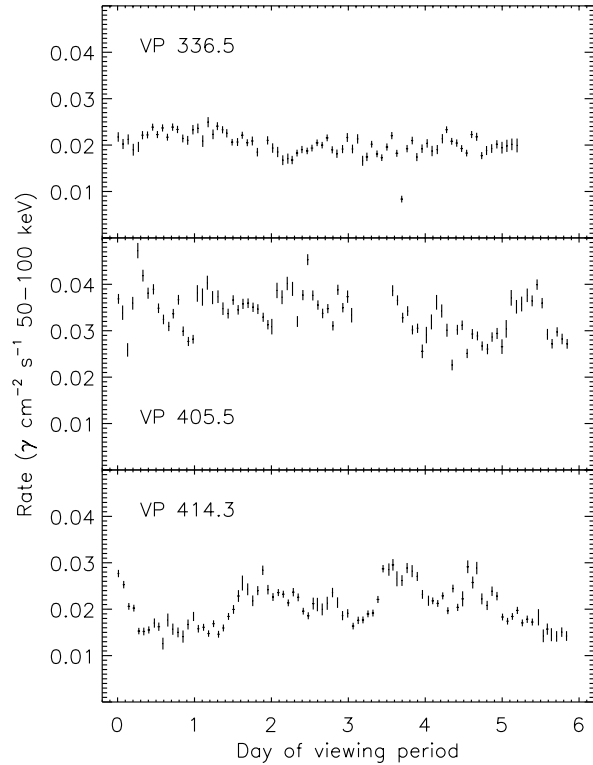


Fig. 2. Photon rate from GRO J1655-40 in the 50-100 keV energy band. Rates are computed once per orbit (approximately 94 minutes). Starting times in the three panels are TJD 9568.65, 9693.64, and 9805.66 respectively.

The light curve is shown in Figure 2 for the three brightest periods. These observations each started 6 or 7 days after the BATSE detection of a large outburst and are near maximum intensity of the outburst. Intensity variations with time are somewhat different in the three outbursts. VP 336.5 shows only slight variations in flux throughout this observation, whereas VP 414.3 shows distinct variations on a time scale of several orbits. The rate in VP 405.5 is slightly higher than in the other two viewing periods with variations of an amplitude similar to VP

414.3. The minimum detectable timescale of variation is on the order of ~ 0.5 days.

A power spectrum was calculated from 8 ms time samples in the 60–80 keV band to search for fast timing noise. No significant noise is detected in the frequency range 0.01 – 60 Hz. We set an upper limit on the fractional rms variation of $<5\%$ of the total flux. For comparison, GRO J0422+32 exhibited rms variations of 40–50% in the 35–60 keV energy band in the same frequency range (Grove et al. 1993).

We find no evidence for line emission to the sensitivity limit of OSSE. The 3 sigma upper limit in the region near 500 keV is $< 4.2 \times 10^{-4} \text{ } \gamma \text{ cm}^{-2} \text{ s}^{-1}$ in one day. The upper limits for the summed data over each viewing period shown in Figure 1 are 2.3×10^{-4} , 2.9×10^{-4} , and $2.2 \times 10^{-4} \text{ } \gamma \text{ cm}^{-2} \text{ s}^{-1}$ respectively.

4. Discussion

GRO J1655-40 is a binary system with eclipses observed at optical wavelengths (Bailyn et al. 1995b). The duration of the optical eclipse is on the order of 4 hours. There is no compelling evidence for eclipsing of the hard X-ray emission. Counting rates are peculiarly low for one orbit in VP 336.5 (day 3.7 of the viewing period), but this is not in phase with the optical eclipse. Variations are evident in VP 414.3. Lower X-ray fluxes in VP 414.3 occur near the time of each of three eclipses. However, these minima are much longer than the optical eclipse and similar behavior is not observed in the other two viewing periods. It is therefore likely that these minima are coincidental and not related to the eclipse phenomena. The absence of eclipses in the X-ray band would suggest that the emission region must be extended and not isolated to the Comptonization region close to the black hole. Possibilities for an extended emission include a hot corona extending well above the accretion disk (Haardt et al. 1993), bulk Comptonization from a post shock, expanded emission region near the black hole (Chakrabarti & Titarchuk 1995), or from the gas jets which are responsible for the radio emission.

The spectrum of GRO 1655-40 is well fit by a power-law with a spectral index $\gamma \sim 2.7$. Other sources with similar spectra include GRS 1009-45 ($\gamma = 2.6$) and 4U 1543-47 ($\gamma = 2.7$), both detected to 300 keV (Harmon et al. 1993), and Nova Muscae ($\gamma = 2.4$) detected to ~ 500 keV (Goldwurm et al. 1992, Sunyaev et al. 1992). This spectrum is distinct from X-ray nova such as GRO J0422+32 shown in Figure 3 (Kroeger et al. 1995) which is well fit by a harder power-law below 200 keV, then rolls off with a shape characteristic of a Comptonization spectrum. The functional form fit to the data shown in Figure 3 is a power law times an exponential cut-off term. Measurements of GRO J0422+32 using the Mir-Kvant observatory (Sunyaev 1993) and SIGMA instrument (Roques 1994) show that spectrum flattens to a simple power-law shape in the

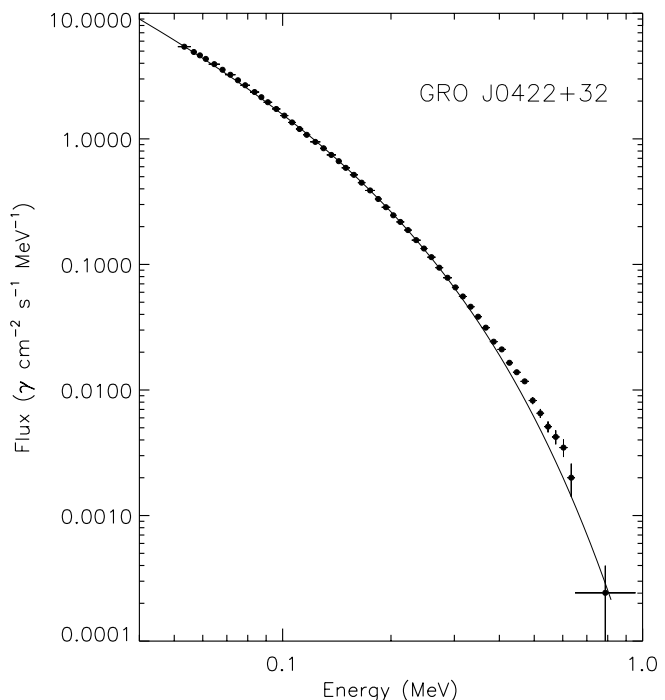


Fig. 3. Energy spectrum of GRO J0422+32 over the time interval from 12 Aug – 17 Sep 1992 (GRO viewing periods 36, 36.5, 37 and 39). It is fit with an exponentially truncated power law ($\gamma = 1.36$, $kT=119$ keV).

20 – 100 keV energy band with an index of $\gamma \sim 1.5$. The Comptonization shape is relatively common among X-ray transients such as sources GRO J1719-29=GRS 1716-249, GX 339-4 (Harmon 1993).

There appear to be two classes of emission from X-ray transients. GRO J1655-40 belongs to the class with soft power-law spectra extending well above 200 keV and spectral index $\gamma > 2$. GRO J1655-40 is the strongest detection in this class of events to date, and shows no indication of a break in the power-law spectrum through at least 600 keV. The second class of emission is better represented by a thermal Comptonization spectrum. It is clear that these hard power-law spectra roll off with a characteristic cut-off temperature $kT \sim 100$ keV. GRO J0422+32 is the strongest detection in this class in a similar energy range to date.

The lack of line features in GRO J1655-40 is also noted. Broad line features have been observed from Nova Muscae around 480 keV (Goldwurm 1992, Sunyaev 1992). This feature was observed in only one 13 hour period out of 8 observations by SIGMA in the first 45 days after the outburst. A similar feature in the GRO J1655-40 spectrum would have been easily detectable by OSSE. OSSE has observed GRO J1655-40 for a total of 17 days in each of three viewing periods with primarily only orbital gaps (30–40 minutes) in exposure during each observation.

We conclude that transient line emission in GRO J1655–40 is either non-existent, present but less than the upper limits we have determined, or a rather rare transient phenomenon. This is interesting in light of the spectral similarity with Nova Muscae. However, other properties such as the light curves in the two transients also differ, GRO J1655–40 is recurrent *vs.* Nova Muscae which is exponential, and thus possible transient line emission may be best associated with something other than spectral shape.

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References

- Bailyn, C. et al., 1995a, IAU Circ. No. 6173.
 Bailyn, C.D., et al., 1995b, Nat 374, 701.
 Chakrabarti, and Titarchuk L., 1995, in press.
 Haberl, F., et al., 1989, ApJ, 343, 409.
 Harmon, B.A., et al., 1995, Nat 374, 703.
 Harmon, B.A., et al., 1993, AIP Conf Proc 304, 210, Ed. Fichtel, Gehrels, and Norris, AIP Press.
 Haardt, F., et al., 1993, ApJ, 411, L95.
 Hjellming, R.M., et al., 1995, Nat 375, 464.
 Hua X., & Titarchuk, L., 1995, ApJ, 499, 188.
 Goldwurm, A., et al., 1992, ApJ 389, L79.
 Grove, J.E. et al., 1993, AIP Conf Proc 304, 192, Ed. Fichtel, Gehrels, and Norris, AIP Press.
 Kroeger, R.A. et al., 1995, ApJ, in preparation.
 McKay, D., et al., 1994, IAU Circ. No. 6062.
 Roques, J.P., et al. 1994, ApJ Sup, 92, 451.
 Rubin, B.C., et al., 1992, AIP Conf Proc 280, 381, ed. Friedlander, Gehrels, and Macomb, AIP Press.
 Sunyaev R. & Titarchuk, L., 1980, Ast. Ap. 86, 121.
 Sunyaev R.A., et al., 1992, ApJ, 389, L75.
 Sunyaev R.A., et al., 1993, A&A, 280, L1.
 Tingay S.J., et al., 1995 Nat 374, 141.
 Titarchuk, L., et al., 1994 ApJ, 434, 570.
 Zhang, S.N., et al., 1994, IAU Circ. No. 6046.